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PhD progress update Gamma measurements of ICF capsule physics

Kevin Meaney

Feb 2019

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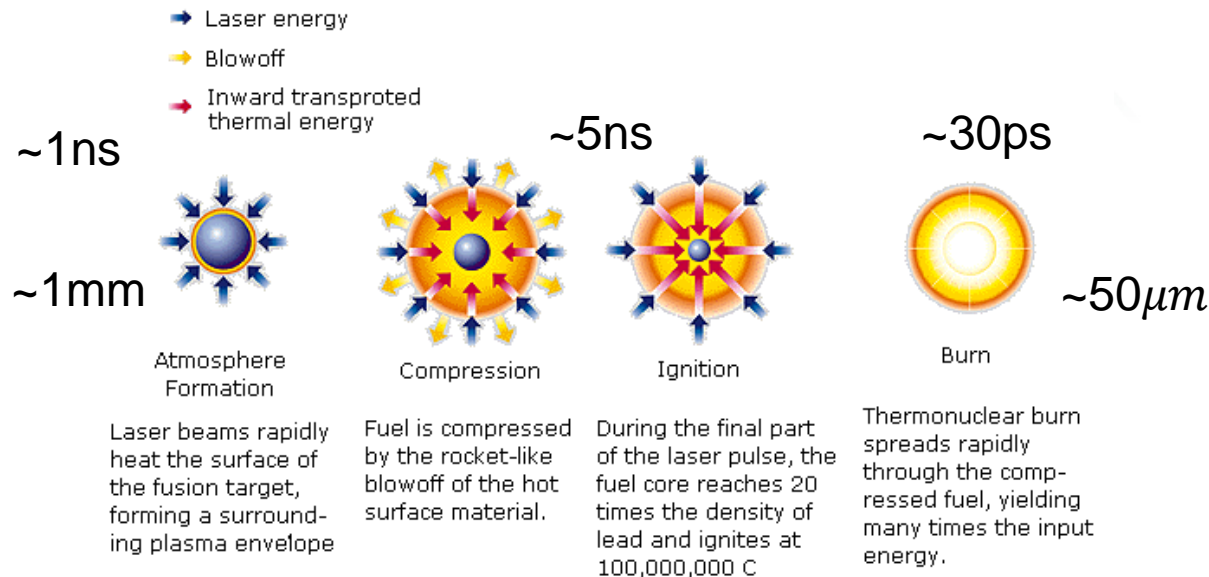
Outline

1. **Review thesis plan**
2. Aerogel Cherenkov detector
3. Carbon gammas for capsule dynamics
4. OMEGA mix experiments
5. Looking forward

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Nuclear processes are fast – can do fusion before object blows apart: Inertial Confinement Fusion

The Inertial Confinement Fusion Concept



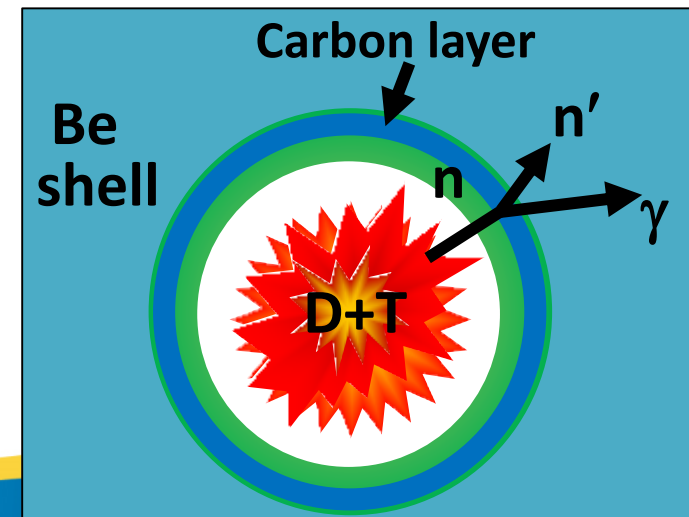
Schematic of Inertial Confinement Fusion, Lawrence Livermore National Lab

- Direct Drive - hit capsule directly with UV laser – more energy coupled
 - At OMEGA laser facility
- Indirect Drive – heat hohlraum, makes x-ray heat bath which hits capsule – more symmetric
 - At National Ignition facility

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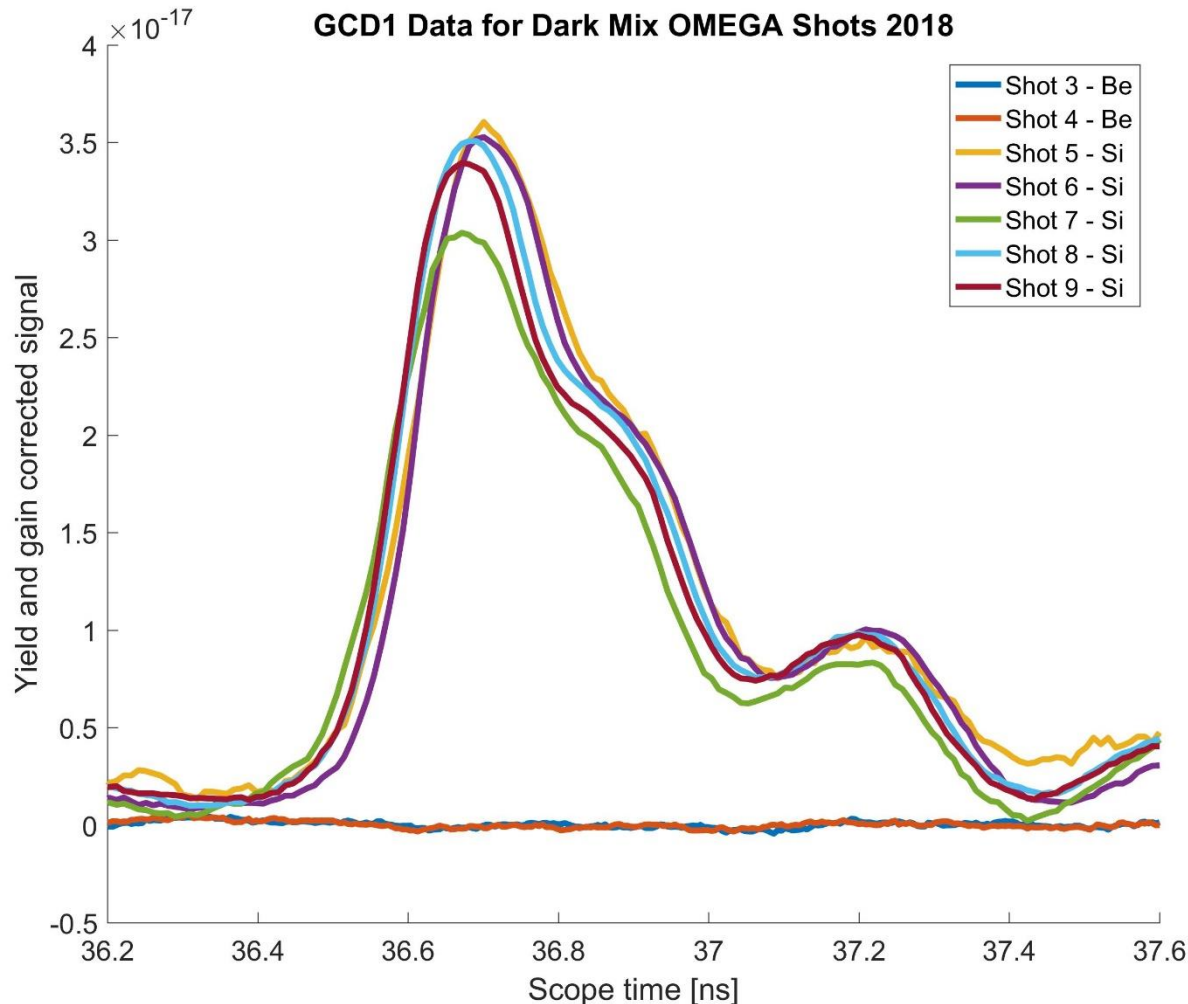
Use neutron induced gamma rays off a placed layer as mix diagnostic

- Understanding mix of capsule is one of the core issues of ICF
- Other mix diagnostics require material to be well mixed and heated to keV temperatures
 - Separated reactants/X ray dopants
- 14 MeV DT fusion neutrons inelastic scatter with carbon to produce 4.4 MeV gamma
- Placed carbon layer in beryllium capsule (transparent to neutrons) gives areal density of placed layer
 - Can be used as cold/dark mix diagnostic
- Fabricated capsules for shot day in July 2018



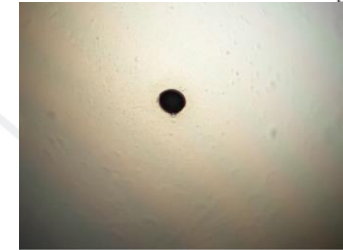
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OMEGA shot day July 2018 - Dark Mix capsules were duds

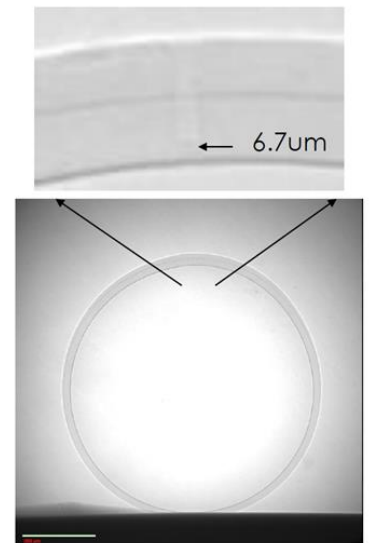
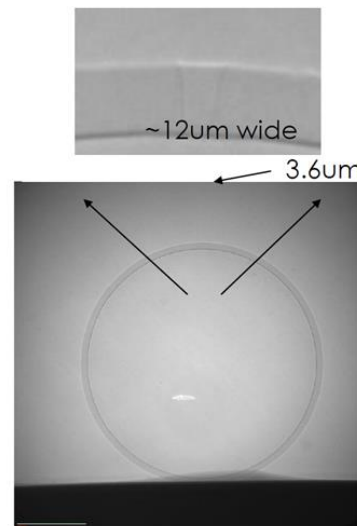
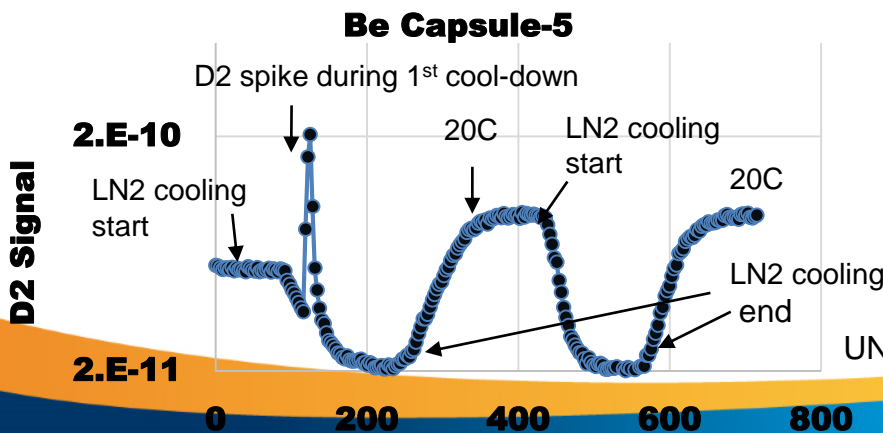


Dark Mix shot day had complex capsules design, lead to shot day failure

- Layering beryllium-carbon-beryllium difficult
 - Were able to create only a couple of capsules
- Capsules are impermeable to diffusion gas fill
- Require plug – laser drill hole, then filled with polystyrene to appropriate half life
- Plug seems to have failed, possibly due to thermal cycling, capsules held no DT gas when shot
 - 2/8 capsules failed test thermal cycle, 1 half life changed



Half life measurement vs thermal cycle



DD HL ~7 hr before and after DD test

Thesis plan

- Pivot to less risky OMEGA gamma derived mix shot campaigns
 - Time resolved mix
 - Asymmetric mix
- Take technique to isolate carbon gammas and apply it to NIF
 - Use carbon gamma to understand the ablator dynamics
- Incorporate work done on aerogel Cherenkov detectors as part of diagnostic instrumentation

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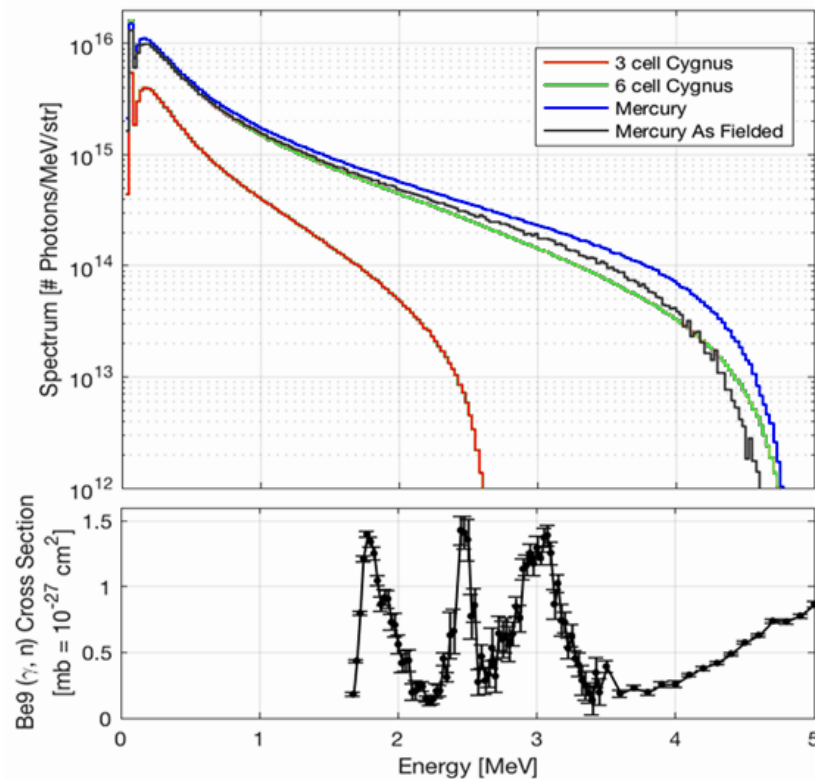
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Brazos project: x-ray source on beryllium to make neutron source

Neutrons Produced (n) is proportional to ${}^9\text{Be}(\gamma, n)$ cross section (σ_γ) * gamma flux (ϕ_γ) * # of available Be target atoms (N_{Be}). ($n \propto \sigma_\gamma \phi_\gamma N_{\text{Be}}$)

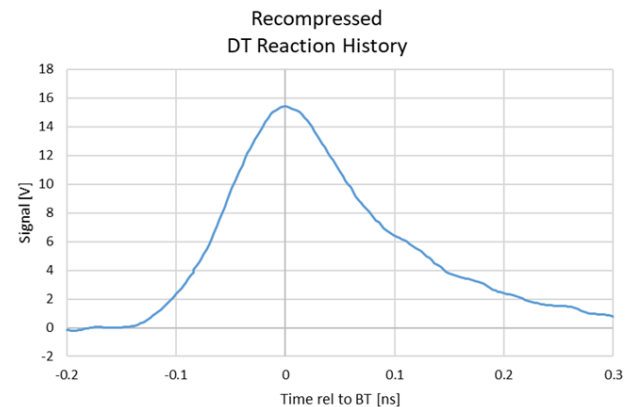
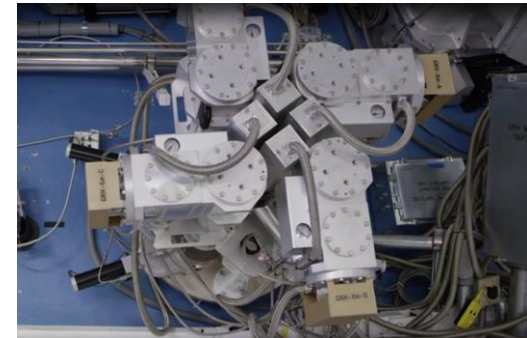
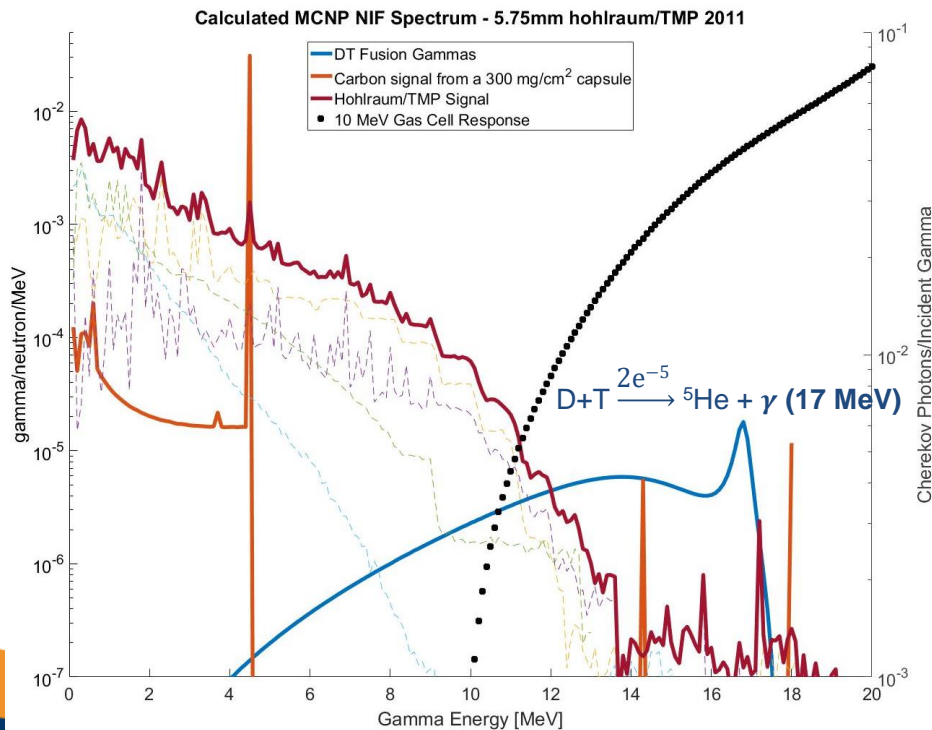
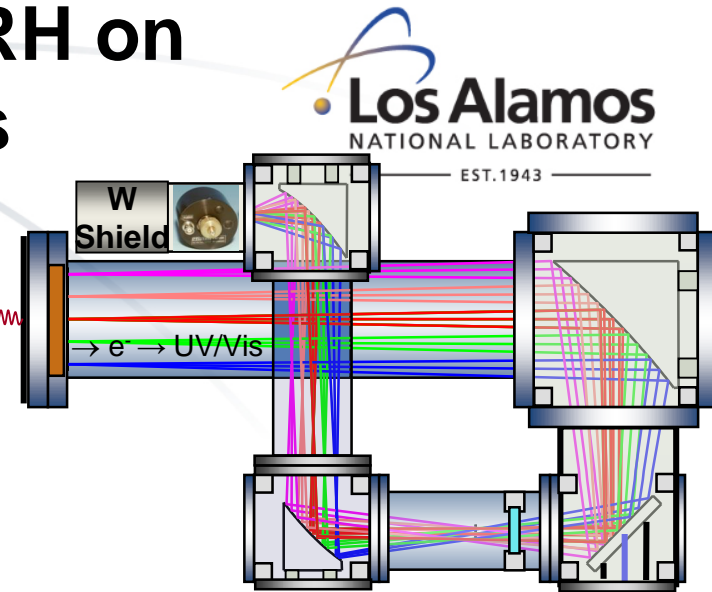


- Photoneutron production by knockout of a neutron from nucleus ${}^9\text{Be}$ has threshold of 1.67 MeV
- Outgoing neutrons have energy between 100 keV and 2 MeV
- Need to understand photon flux coming out above specific energy threshold
- Pulse power machines have shot-to-shot variation in the highest energy photons
 - “Wagglng tail”
- → Cherenkov detector

ENDF VII/B ${}^9\text{Be}(\gamma, n)$ cross section $E_\gamma = 1 \text{ MeV} - 5.5 \text{ MeV}$ with a spectral model

Why use Cherenkov system? GRH on NIF isolates fusion gammas

- Chosen index of refraction of Cherenkov medium only measures photons above chosen energy
- Cherenkov process is inherently fast, can be designed for fast IRF



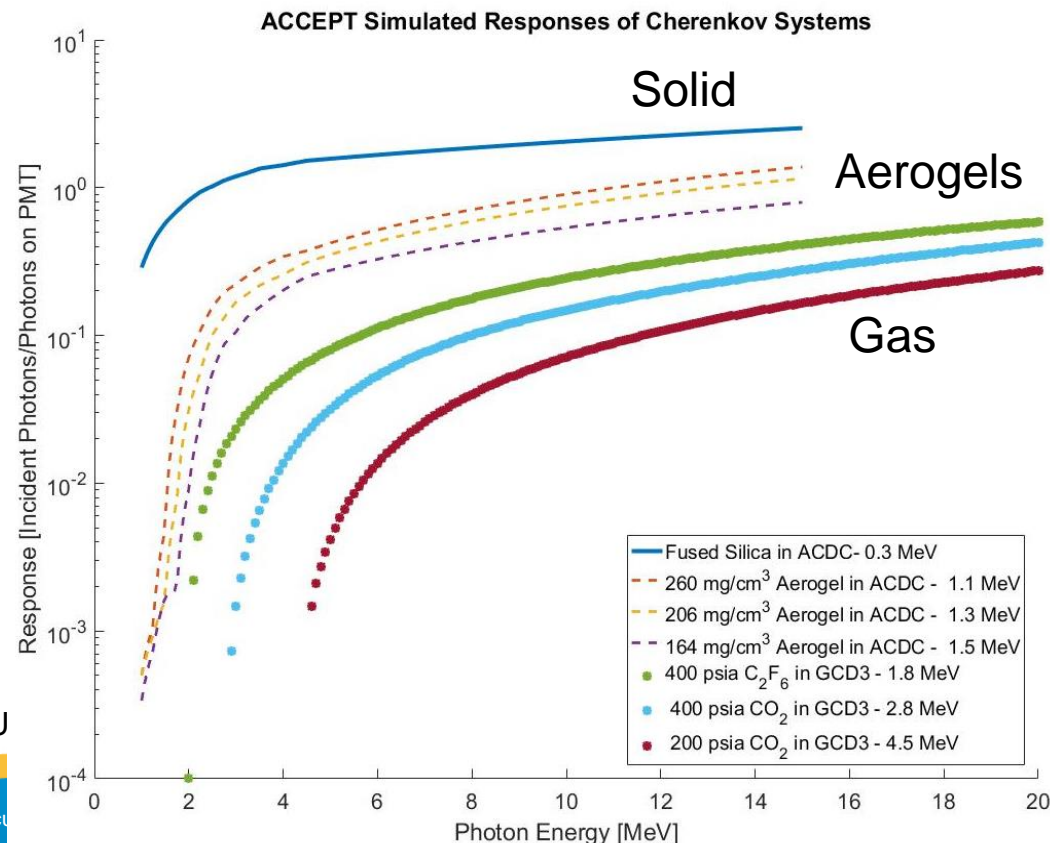
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Aerogel's Cherenkov threshold sits between solids and gas



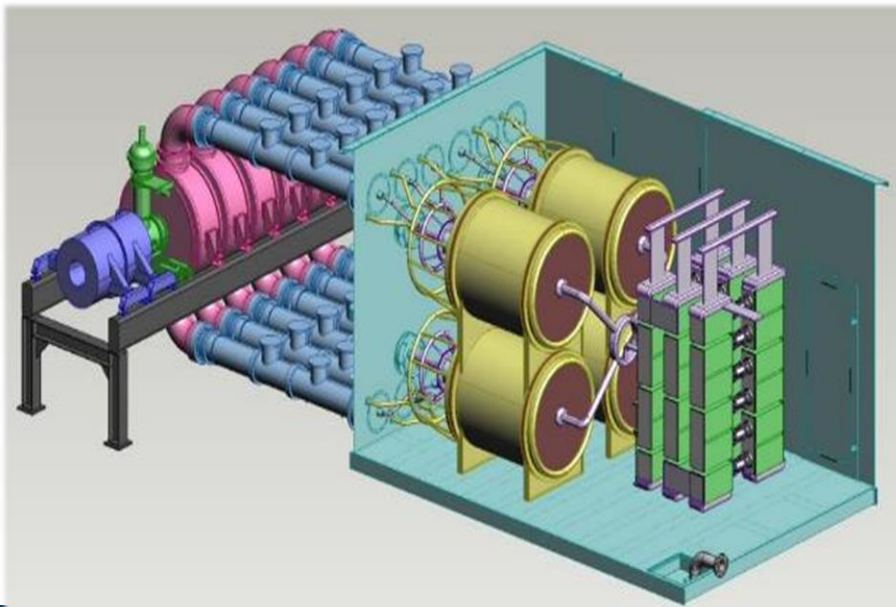
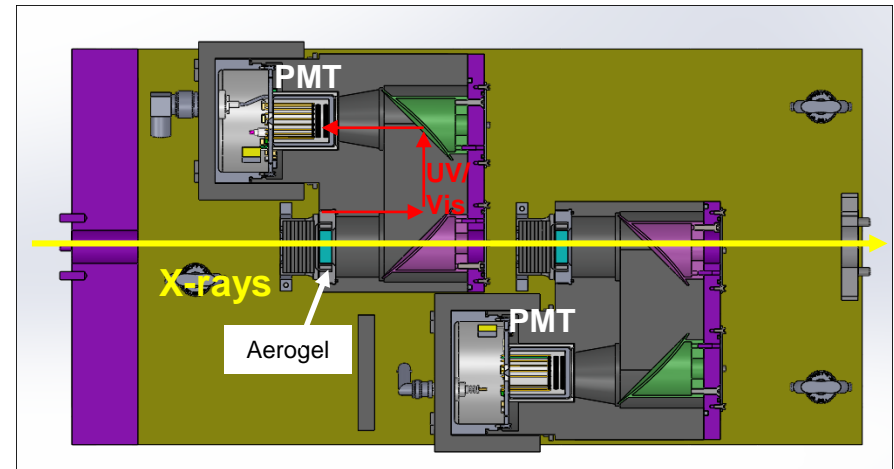
- Solids and liquids have n of 1.3 and larger
 - 0.3 MeV threshold and lower
- Gas can only be so dense, n of 1.02 and lower
 - 1.8 MeV threshold and larger
- Between these thresholds aerogels must be used
 - ~ 1 MeV threshold and larger

- Aerogel has more self absorption
- No gas pressure system
- Aerogels fabrication difficulties
 - Voids, cracks, density non-uniformity
 - Can be improved through time/effort
- Can absorb water
 - <2% mass over month



Aerogels brought to Mercury Inductive Voltage Adder (IVA) pulsed power machine located at Naval Research Lab (NRL) in DC

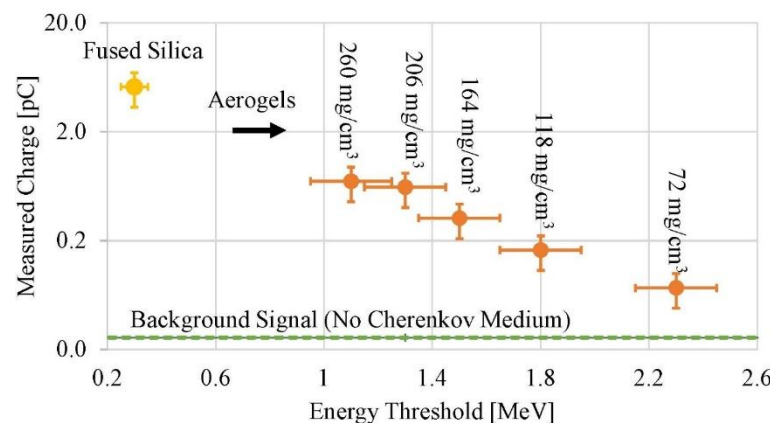
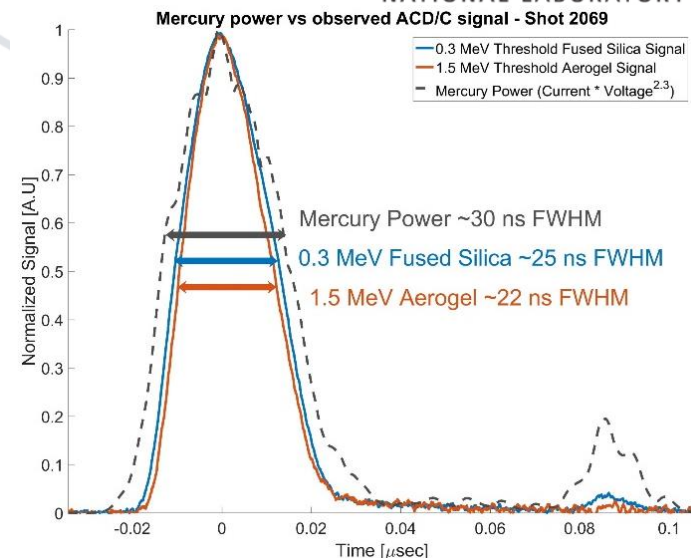
- Aerogel Cherenkov detector has 2 modules, aerogel placed in 1st module, quartz placed in 2nd module
- Aerogel in front swapped out shot to shot, 5 different densities



- Pulsed power machine
- The Mercury machine is capable of producing a photon spectrum with a possible 20 MeV endpoint, but for our purposes, was adjusted to 5 MeV
- Mercury fit with a Large Area Diode that was reusable for all shots (about 6 per day)

Aerogels used to characterize Mercury's x-ray source

- Fielded at NRL for 6 weeks
- Got time resolved x-ray pulses, high signal to noise
- Data used to forward fit spectrum, constrain and improve simulation
 - Meaney, et al Rev. Sci. Instrum. **89**, 10F113 (2018);
- Brazos project awarded Distinguished Performance Award and Award of Excellence from Los Alamos
- Plan to return in April or May to do a pulsed power diode development. ACD may be used at Cygnus in Nevada.



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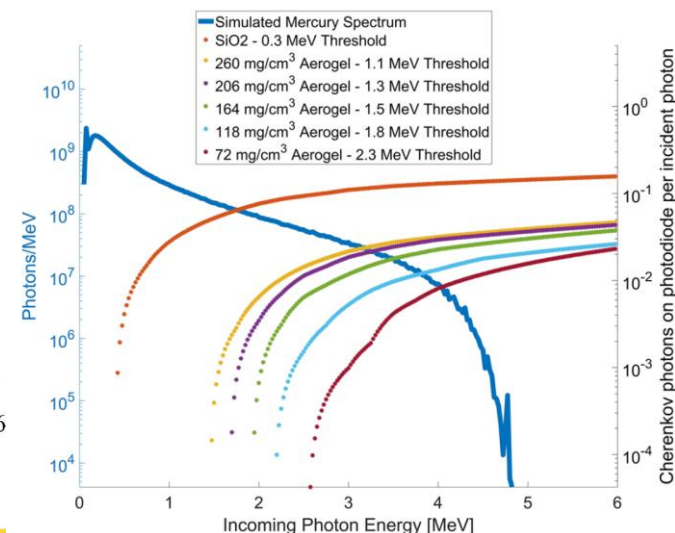


FIG. 5. Particle-in-cell simulated Mercury photon spectrum with ACCEPT response curves.

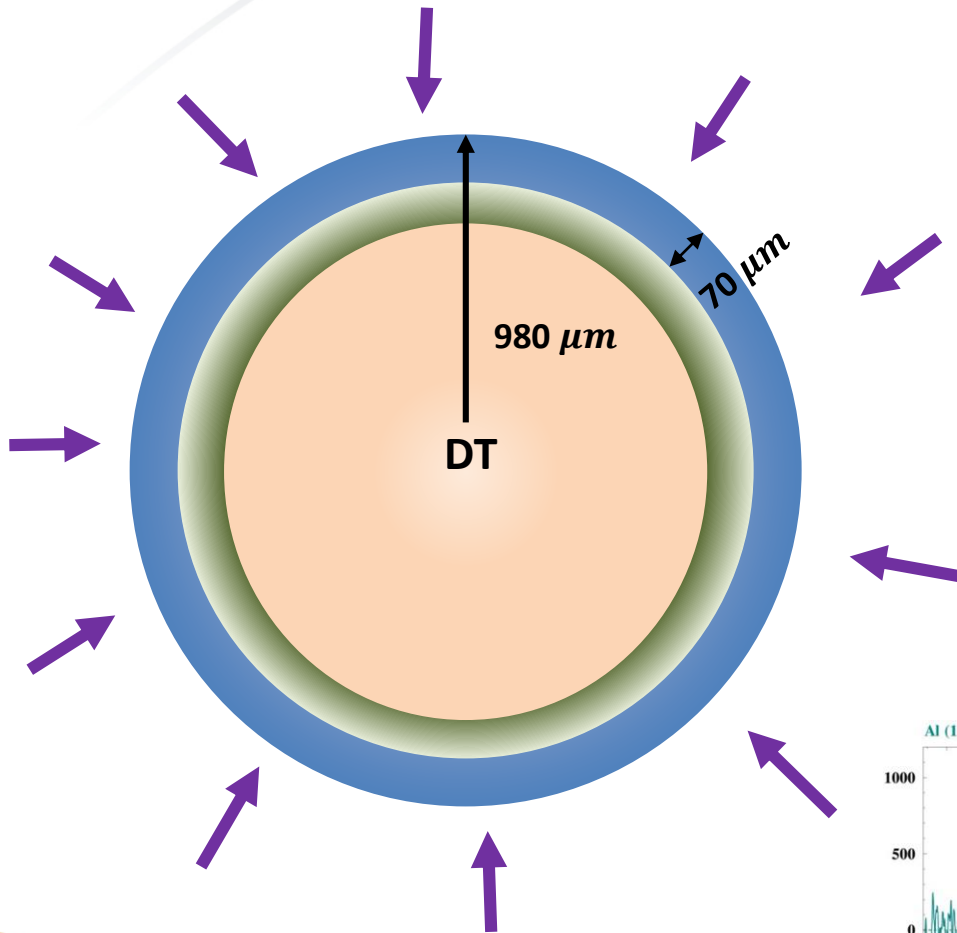
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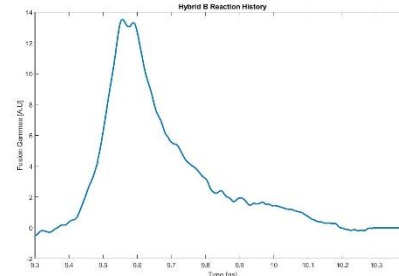
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The ablator transfers x-ray energy to hot spot energy Very few diagnostics look at the ablator

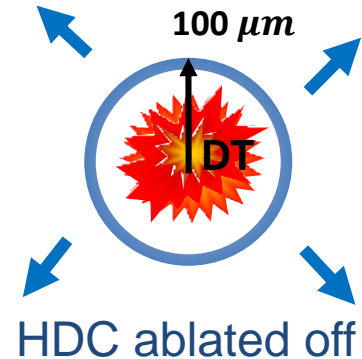
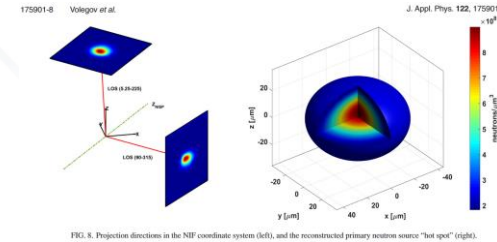
Laser makes ablation front



Reaction history

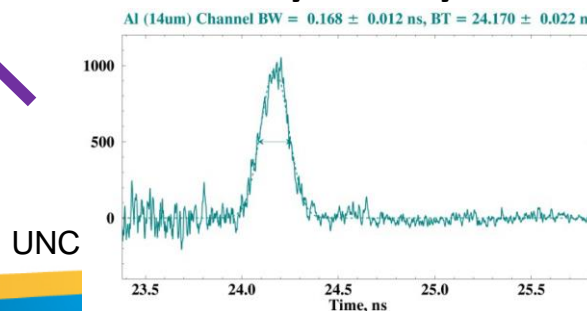


Neutron imaging

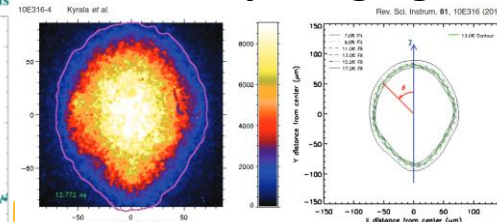


Ablator?

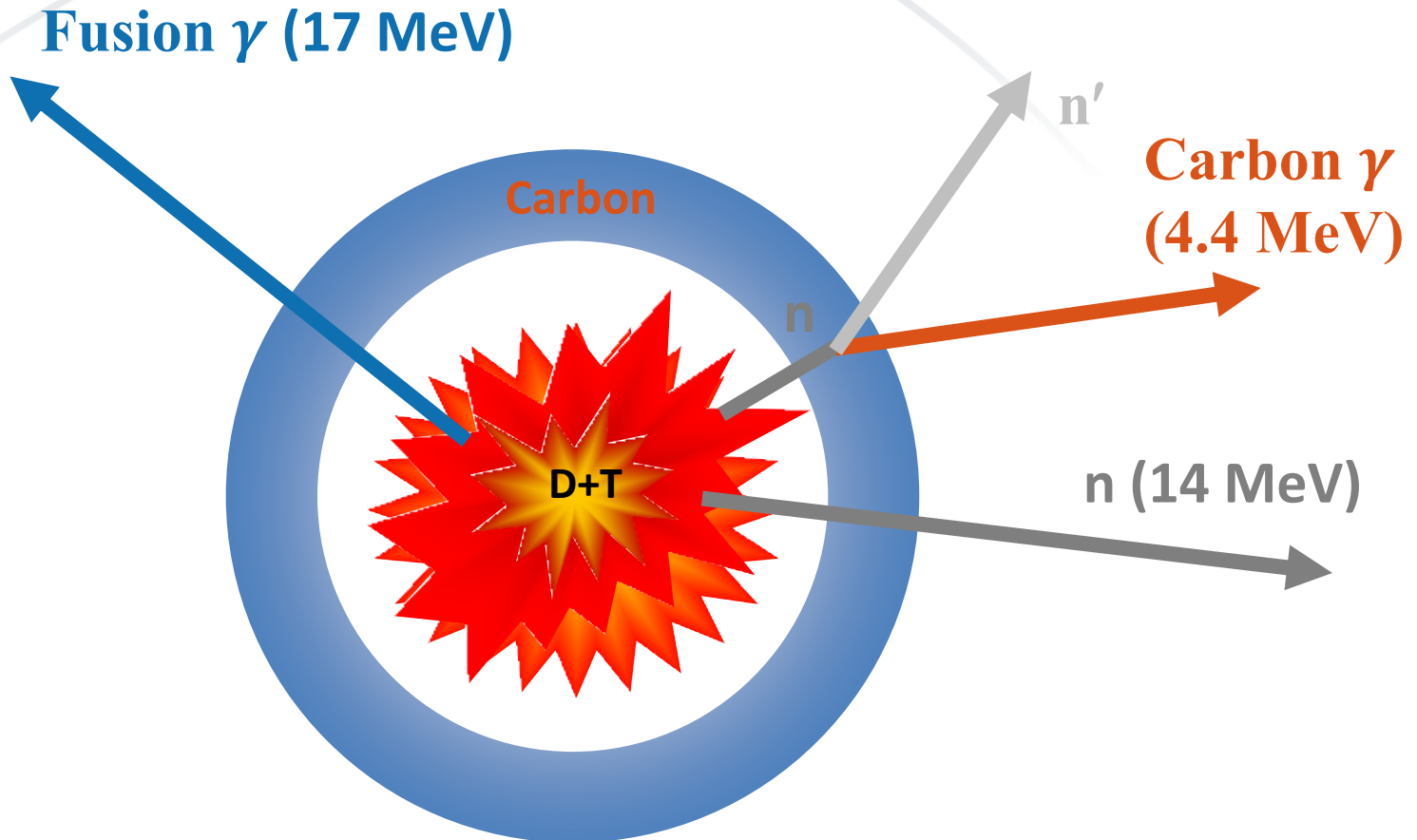
X-ray history



X-ray imaging

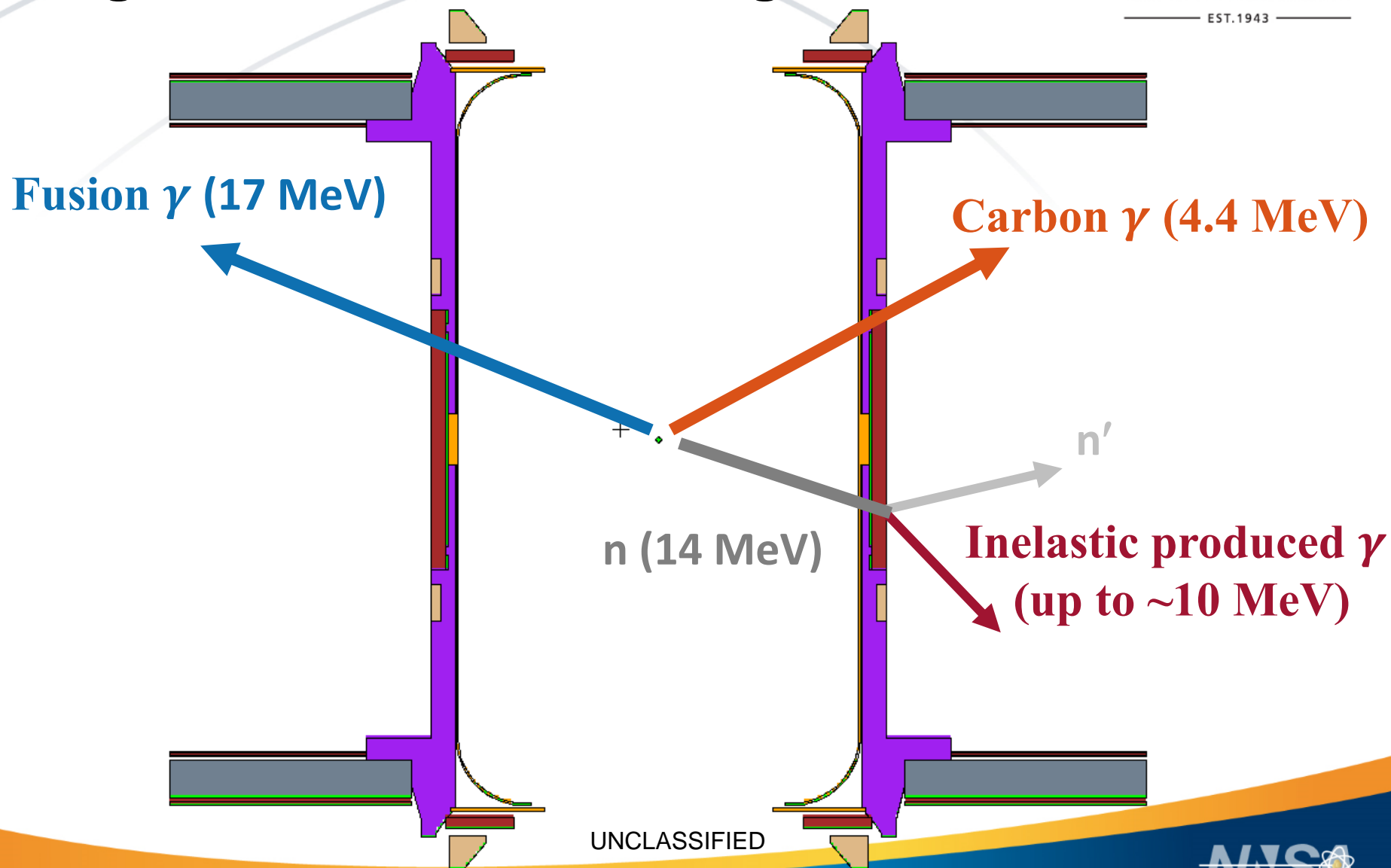


DT fusion neutrons inelastically scattering on carbon emits 4.4 MeV gammas



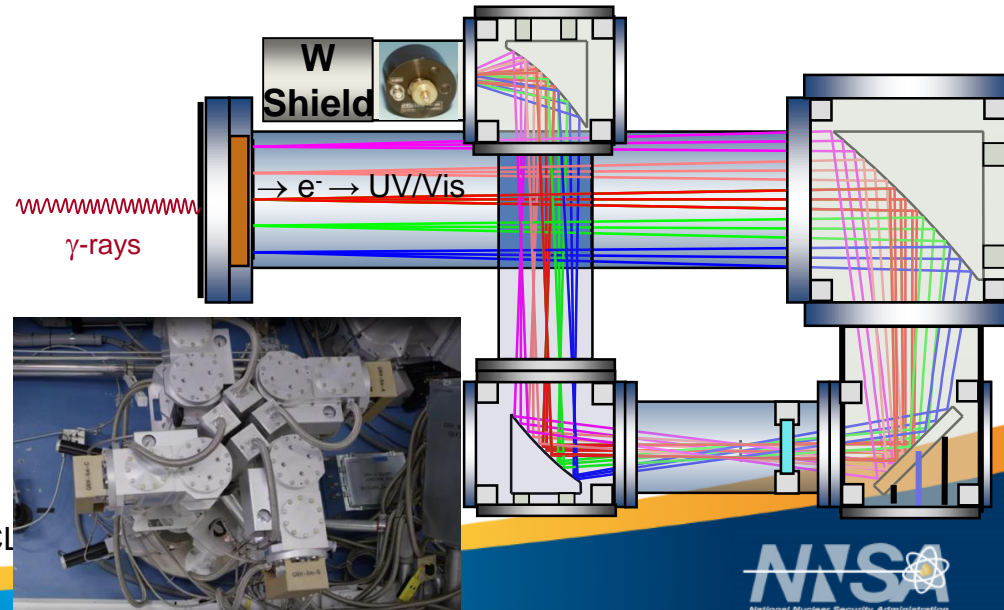
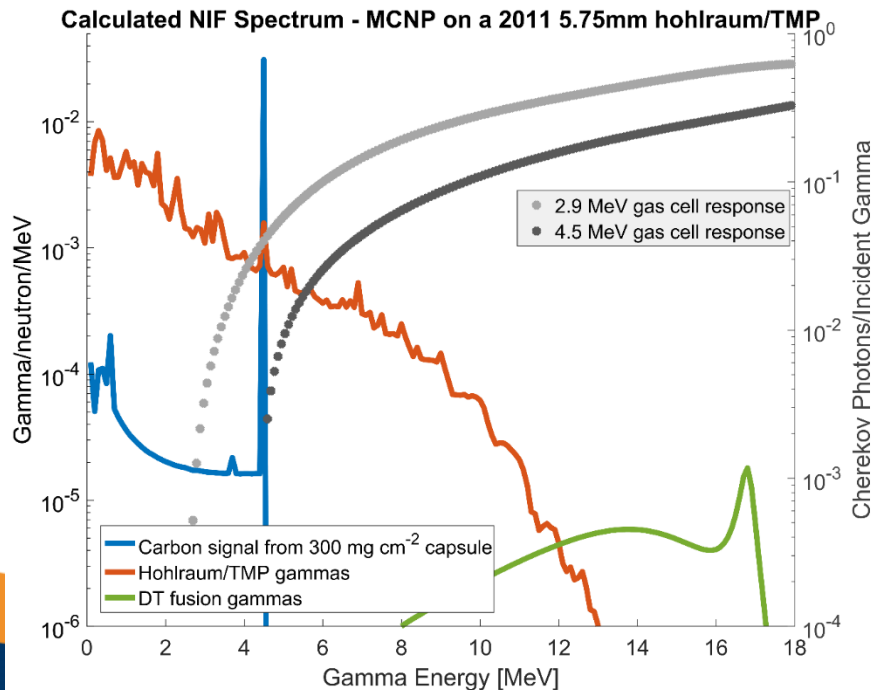
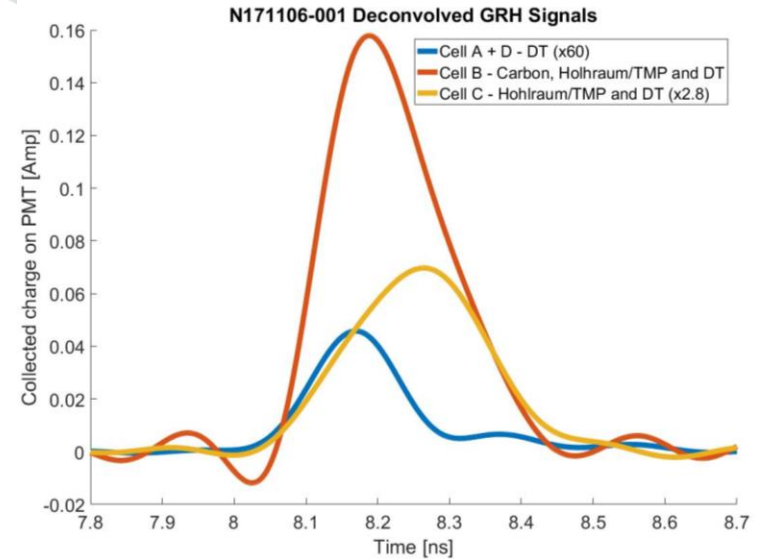
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Carbon gamma competes with n' background from surrounding structure



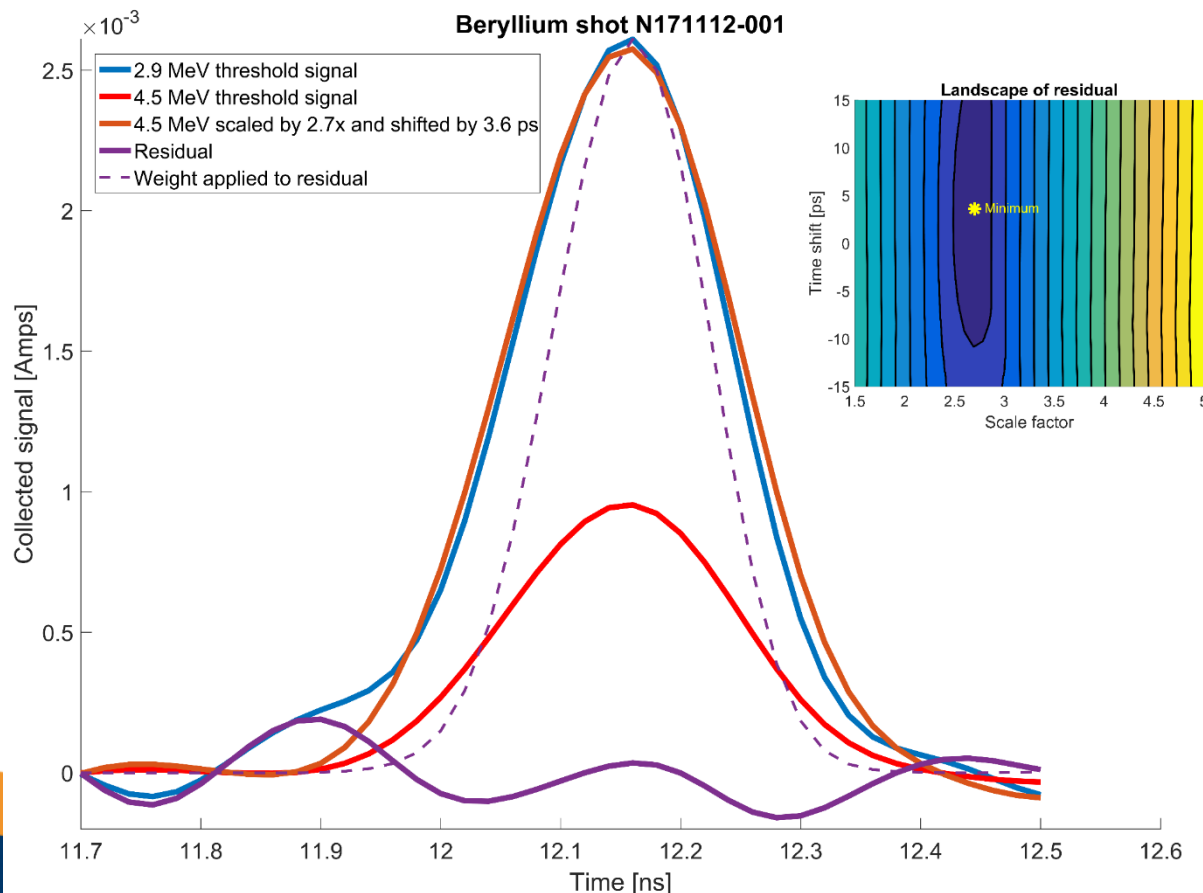
Use different gas pressures to isolate the 4.4 MeV carbon γ from the background

- Deconvolve signal using impulse response of gas cell and PMT
- Can use two gas thresholds, 2.9 MeV threshold and 4.5 MeV threshold to isolate carbon gammas



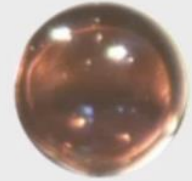
Beryllium capsules used to calibrate a gamma spectrum that has no carbon component

- Beryllium has negligible neutron induced gammas
- Use 4 shots to find what the appropriate scaling factor (2.8) is between the 2.9 MeV and 4.5 MeV signal with no carbon



Capsule Ablators

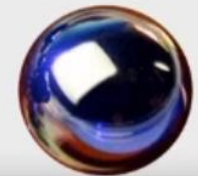
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Beryllium



High Density Carbon

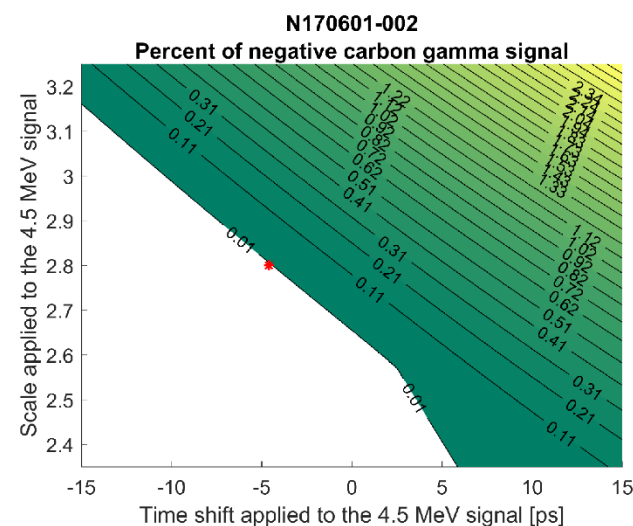
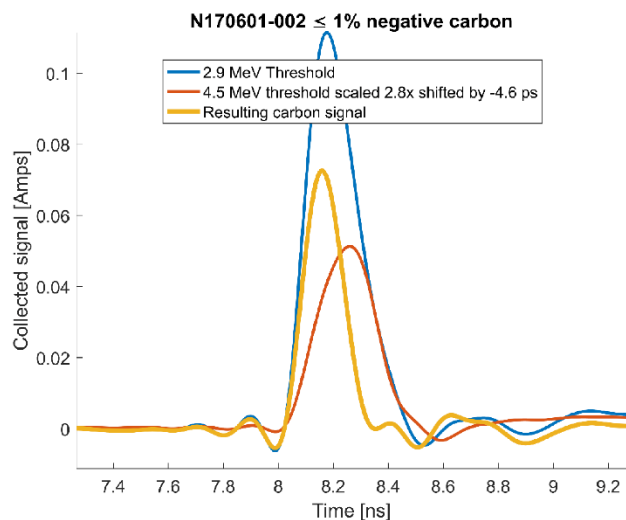
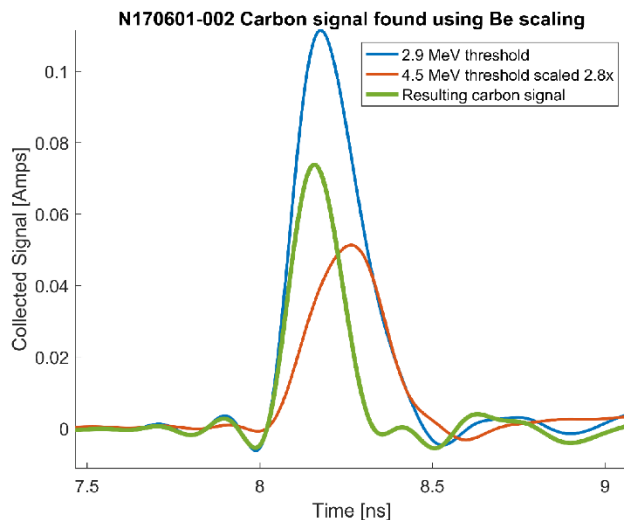


Use scaling factor to apply to other shots with carbon, allow variation to minimize negative carbon signal

Process of isolating carbon gammas submitted to RSI

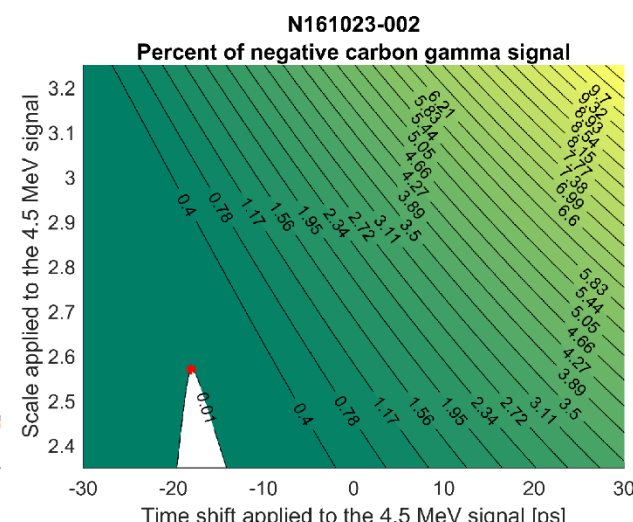
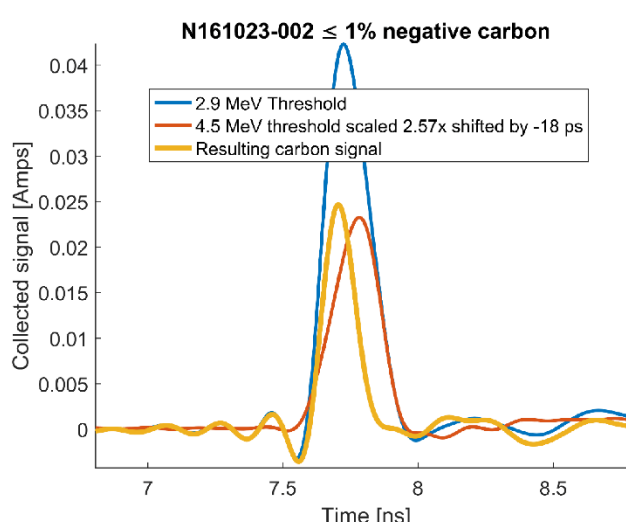
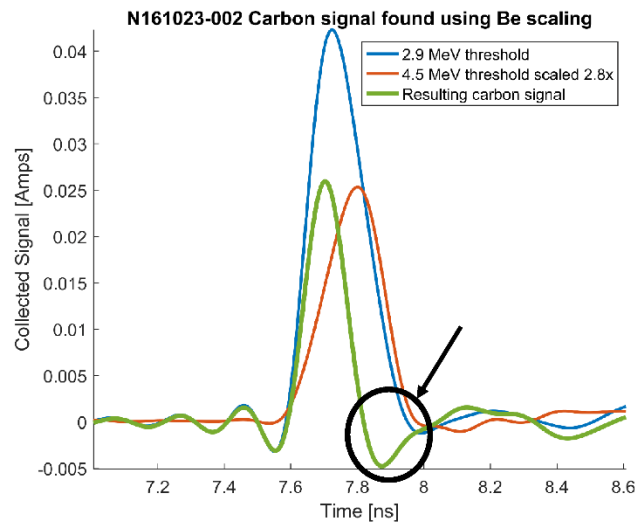
a)

N170601-002 HDC Demo S01a

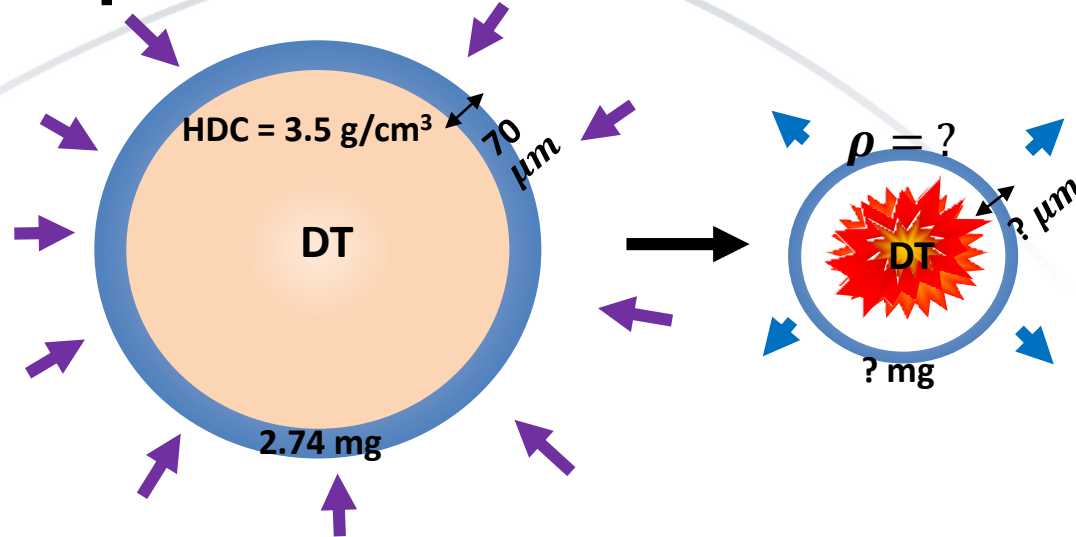


b)

N161023-002 HDC SubScale S06a

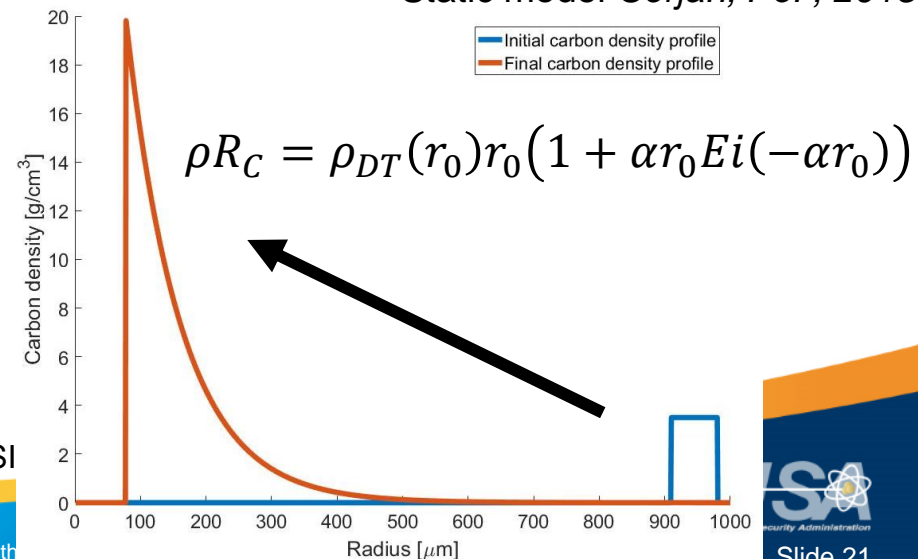


Carbon ρR reflects the mass remaining and compression of the ablator



- Rocket phase → Deceleration phase → Expansion phase → Bangtime
- Too little ρR_C , not enough mass remaining
- For given amount of mass, more ρR_C , the more compression
- Too much ρR_C , too much mass remaining
- Mix may increase ρR_C

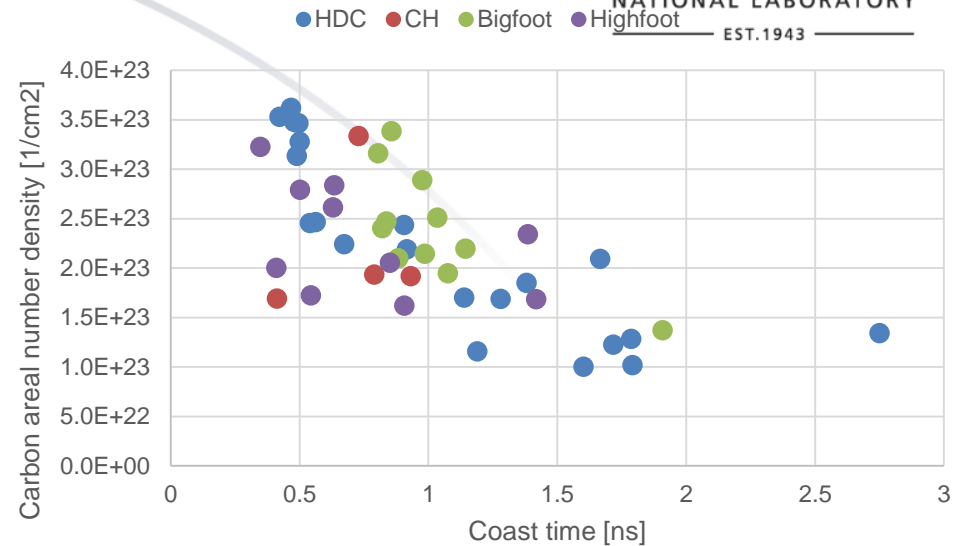
Static model *Cerjan, PoP, 2015*



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Increasing coast time, decreasing carbon ρR ; sensitive measure for ablation pressure

- Coast time is a figure of merit related to peak velocity and total ablation pressure
- Coast time lets hohlraum cool, capsule free to expand, decreasing confinement
- Remaining ablator expands first, directly decreases carbon ρR
- Metric of final compression that other diagnostics can't observe



Hurricane et al, PoP 2017

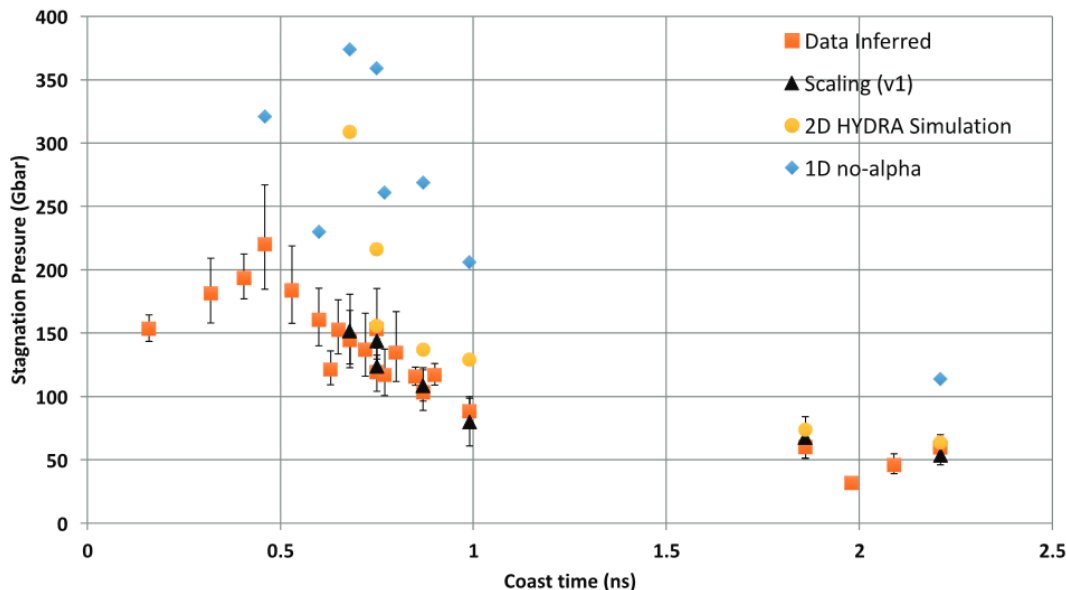
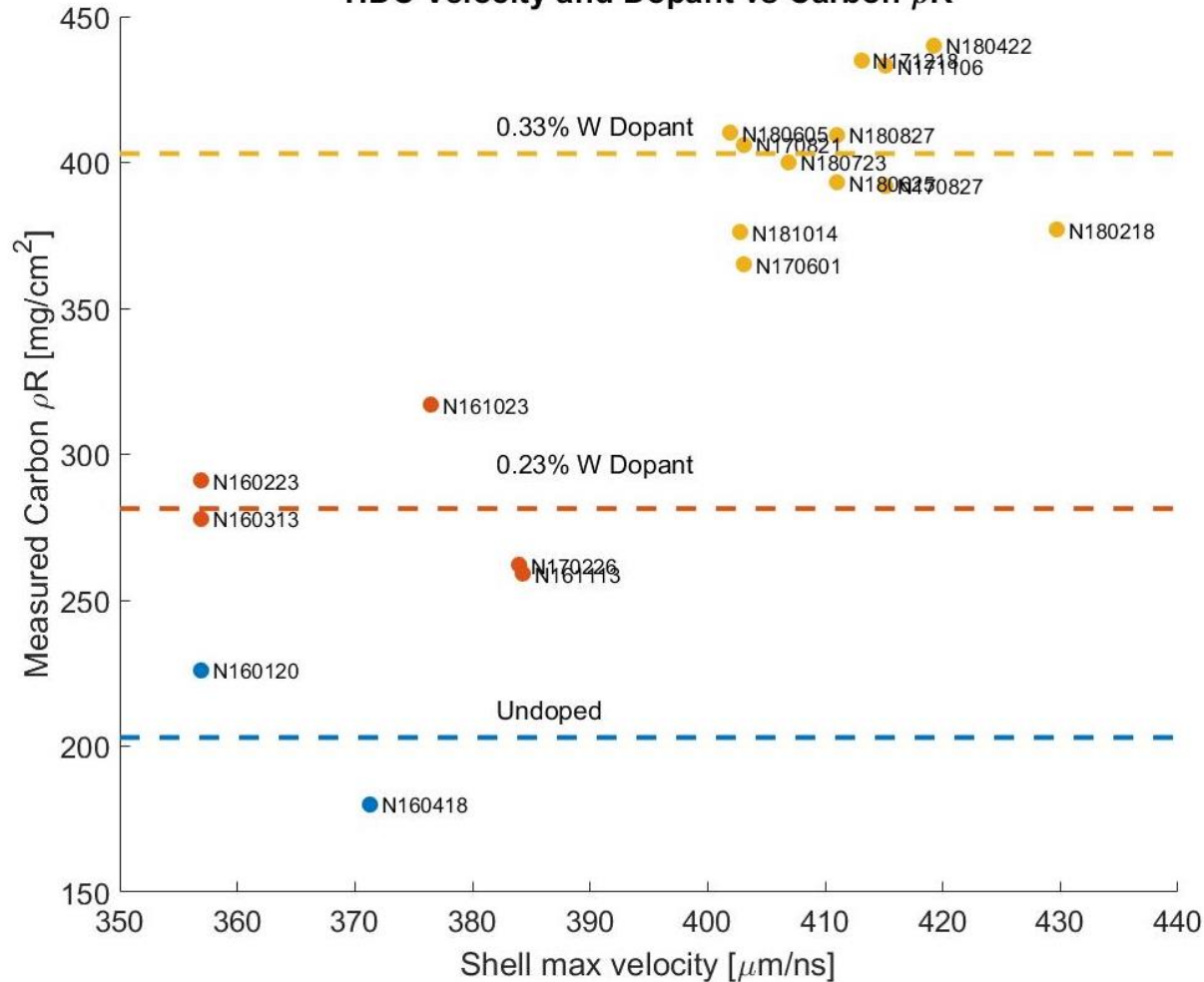


FIG. 6. P_{stag} inferred from high-foot implosion experiments (orange boxes) is plotted versus measured t_{coast} . The results from 2D burn-on post-shot simulations²² are shown (yellow circles) as well as burn-off 1D simulations (blue diamonds) both for a subset of the experiments. Stagnation pressures (black triangles) are calculated with Eq. (11), using the DANTE T_r measurement and inferred v_{imp} , match the inferred stagnation pressure using a single fixed normalization constant. Note, the implosions for which $t_{coast} < 680$ ns had thinner (by 20–30 μm) ablators than those where $t_{coast} \geq 680$ ns. Also, as noted previously¹⁸ fuel compression was observed to dramatically improve when coast-time was reduced from ~ 2 to < 1 ns.

More dopant, larger ρR_c - measuring preheat and adibat

HDC Velocity and Dopant vs Carbon ρR

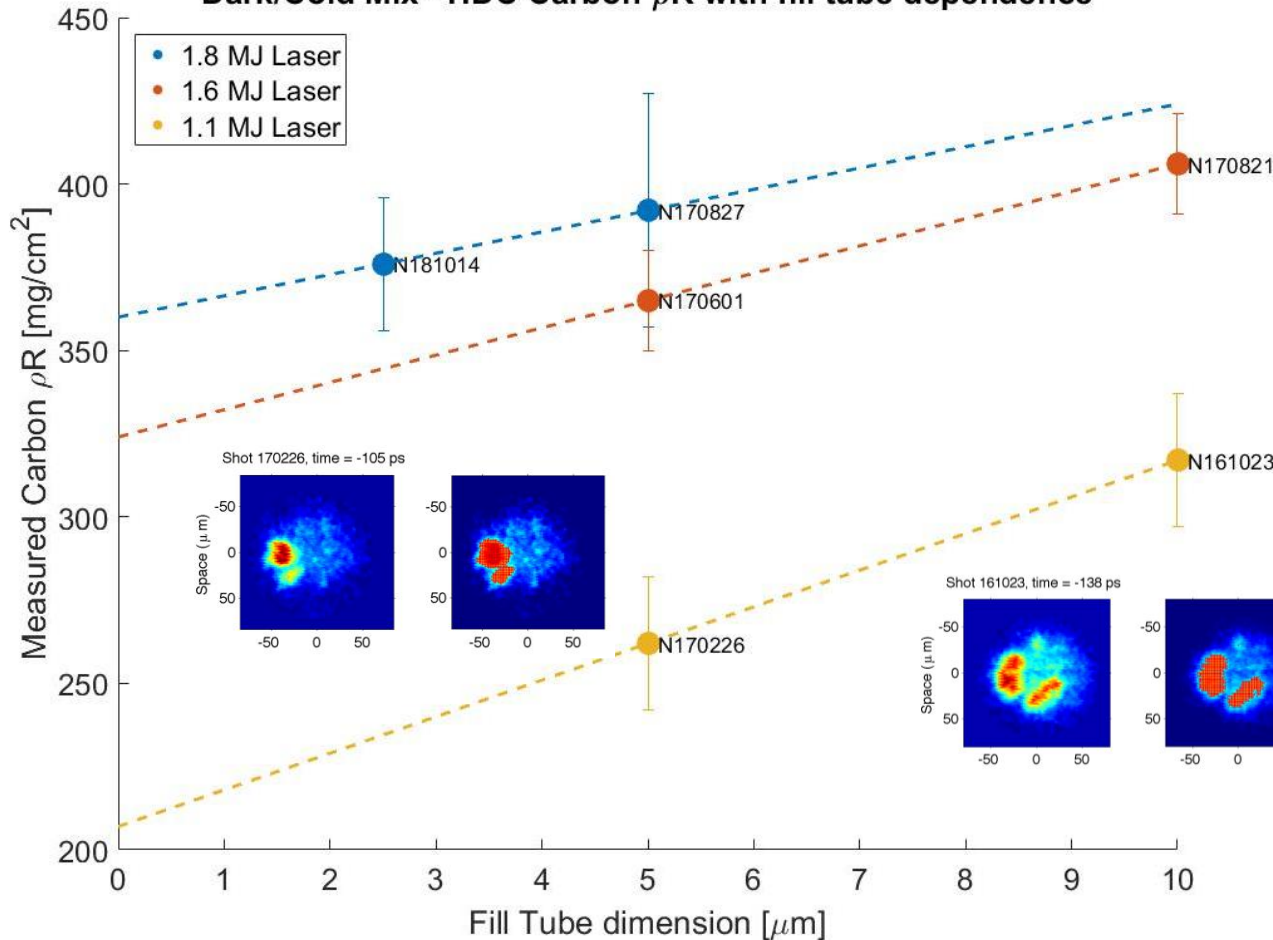


- Preheat and mix free parameters in modeling/simulations
- Dopant placed to shield against preheat
- Increased dopant \rightarrow increasing ablator compression
- Hot spot size has loose correlation
- Including remaining ablator into calculating adibat
- Working with Livermore designers to refine + constrain preheat models

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Smaller fill tube, smaller ρR_c – gives constraint on amount of dark/cold mix

Dark/Cold Mix - HDC Carbon ρR with fill tube dependence



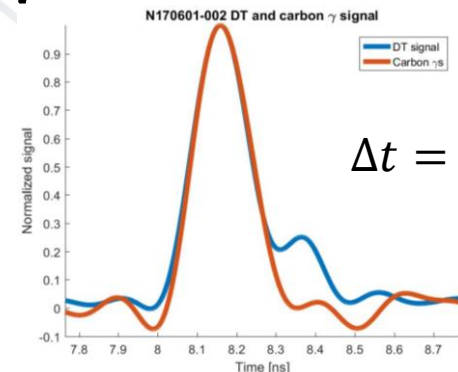
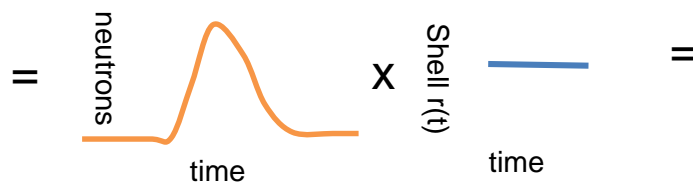
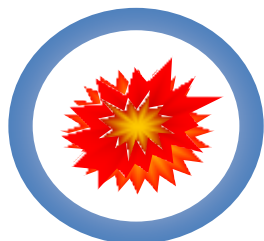
- 1 to 1 comparisons on fill tube shows less ρR the smaller the fill tube
- Fill tube jetting and meteors increase carbon signal
- Independent of temperature/mix
- Used in tandem with x-ray signals to constrain amount of mix
- **These observations and accompanying models have begun to be written into a paper, planning to submit to PoP**

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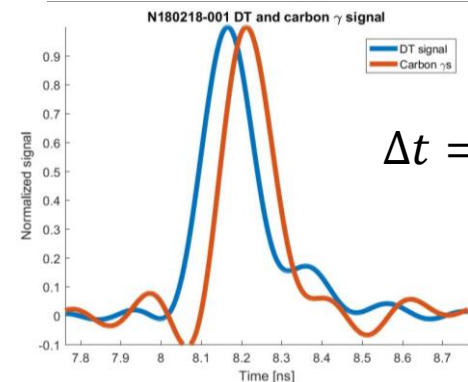
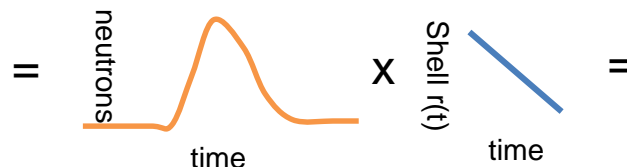
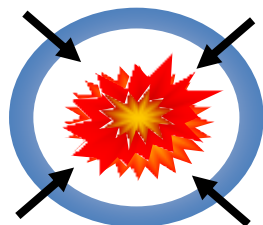
Carbon gamma timing compared to DT peak gives information about shell dynamics

$$C_{\gamma}(t) = RH(t) * \rho R(t) * \sigma_{C\gamma}$$

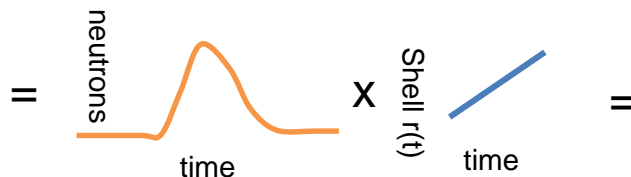
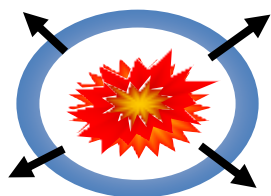
Shell stationary at bangtime (complete stagnation)



Shell moving inward at bangtime



Shell moving outward at bangtime



Not observed.
Predicted in igniting
capsules

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Timing shift can be used to estimate velocity and kinetic energy in ablator at bangtime

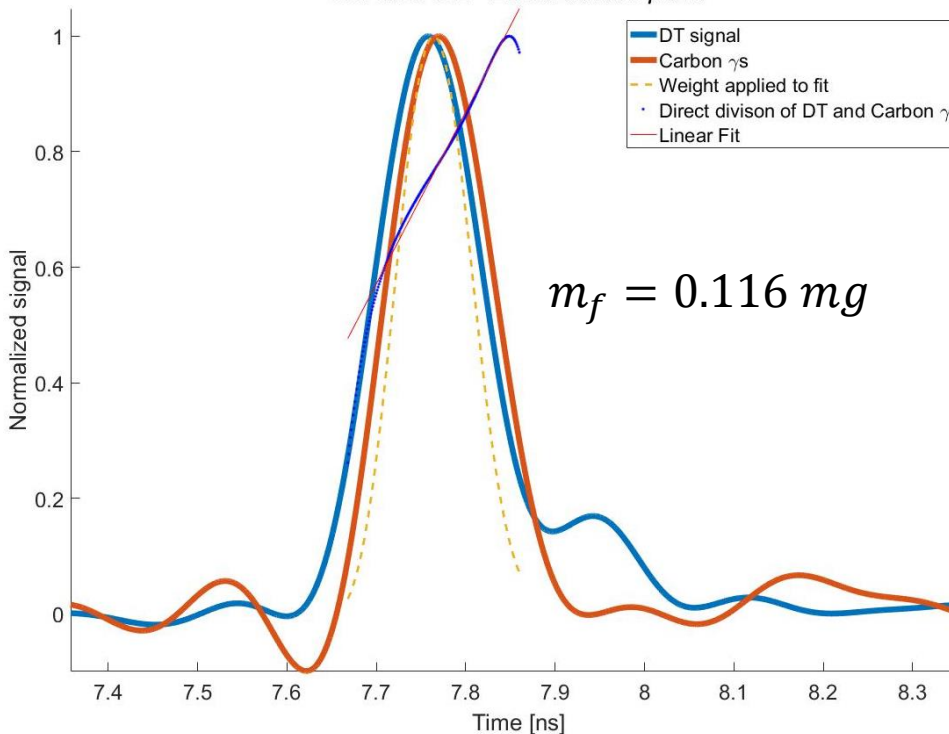
$$\rho R(t) = \frac{RH(t)}{C_\gamma(t)} * \sigma_{C_\gamma}$$

Estimate velocity and residual kinetic energy of ablator

$$v \approx \frac{1}{4} \sqrt{m_f} \frac{\frac{d}{dt} \rho R}{\rho R^{\frac{3}{2}}} \approx \boxed{167 \frac{\mu m}{ns}}$$

$$KE \approx \frac{1}{32\pi} m_f^2 * \frac{\left(\frac{d}{dt} \rho R\right)^2}{\rho R^3} \approx \boxed{0.4 kJ}$$

N171029-002 - Linear ablator ρR fit

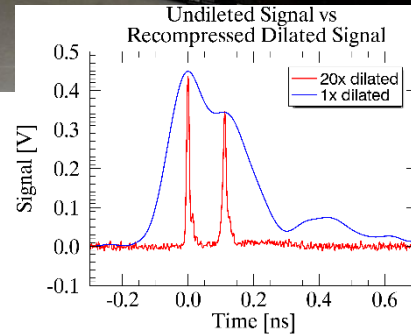
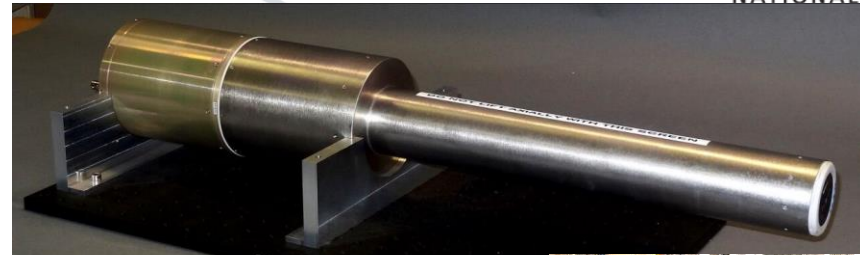
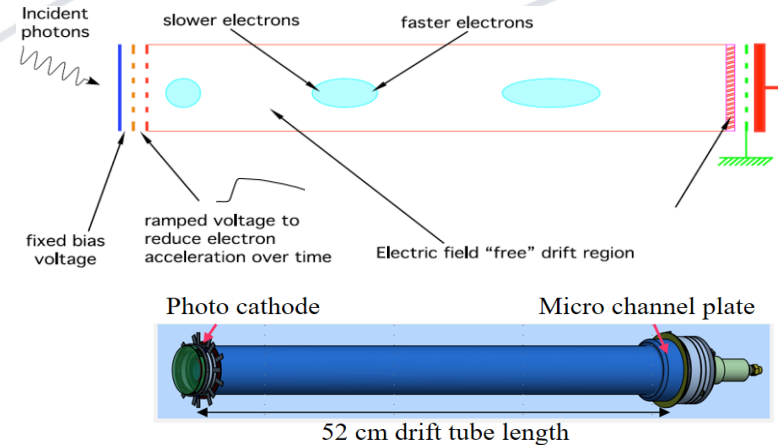


Preliminary simulations suggest faster speeds than observed.

Carbon gamma shift as part of a dynamic model is planned to be written into a paper

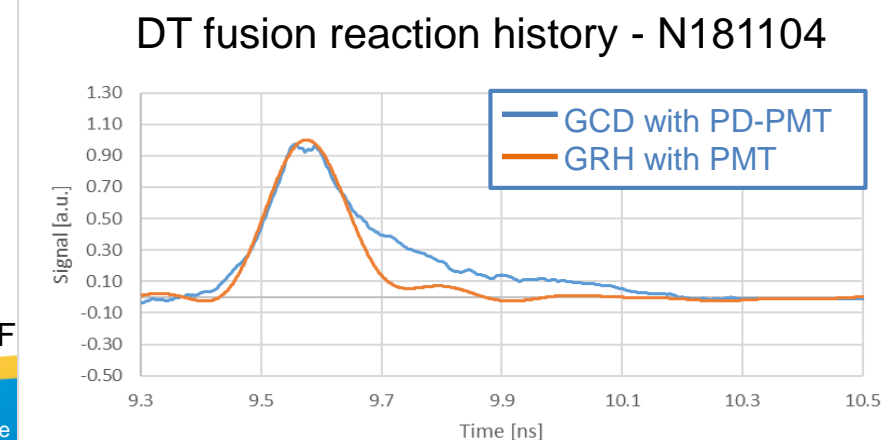
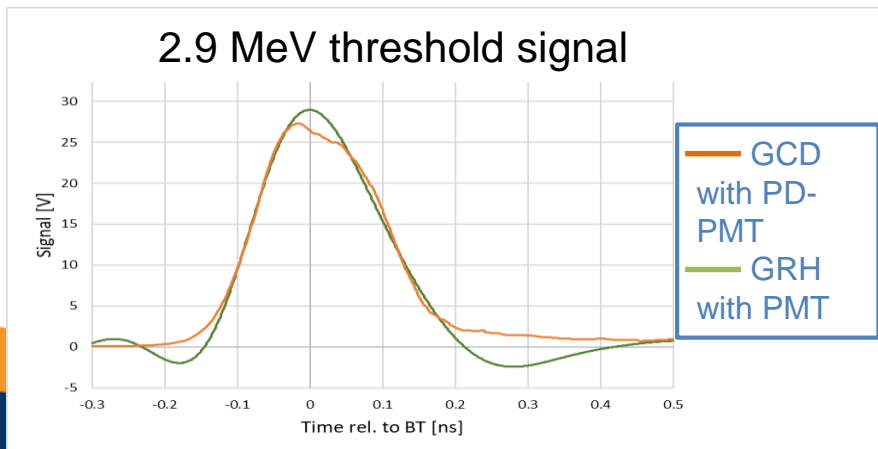
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Pulse dilation PMT is a new technology that will improve carbon γ measurements



H.W. Herrmann, Review of Scientific Instruments **89**, 101148 (2018)
H. Geppert-Kleinrath, Review of Scientific Instruments **89**, 101146 (2018)
S.G. Gales, Review of Scientific Instruments **89**, 063506 (2018)

- PD-PMT improves impulse response function from ~ 110 ps to ~ 10 ps
- Gives higher temporal resolution signals – better carbon γ separation from hohlraum/TMP γ s.



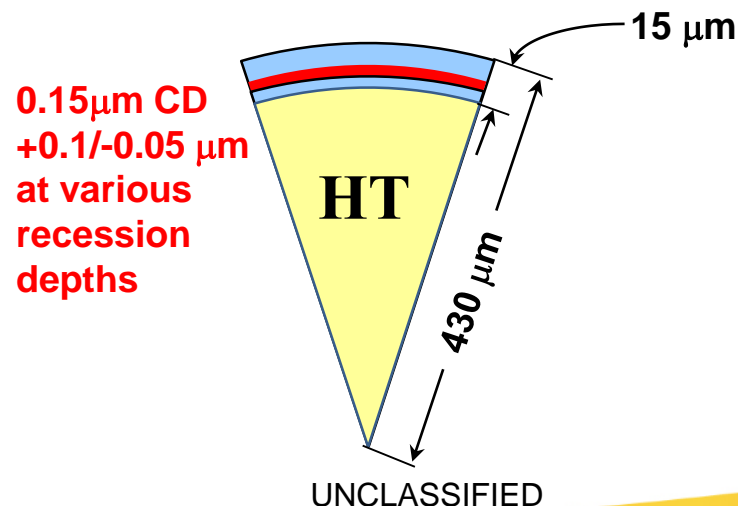
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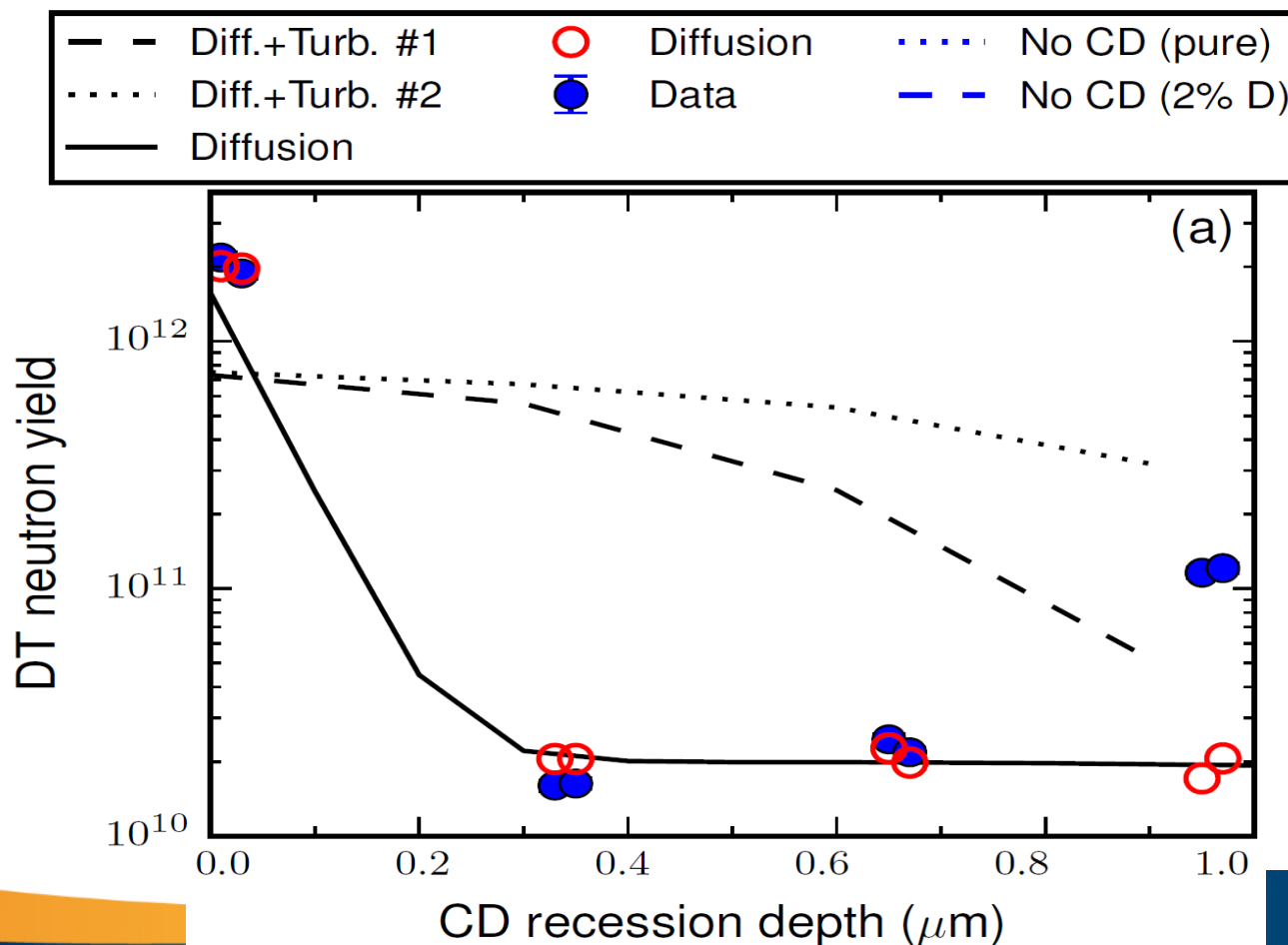
OMEGA mix measurements

- Capsule-fuel a vital point of interest, ICF capsule simulations uses RAGE with uses BHR mix model
 - Reynolds Average Navier Stokes (RANDS)
- Separated reactant experiments
 - capitalizing on the fast response of the gamma detectors
 - Very precise placed layers (150 nm)



OMEGA shots in 2017 gave unexpected results

- Thin deuterium layer showed that capsules were diffusion dominated, not hydrodynamically dominated
- Revealed that some mix mechanism is pulling material from deeper in the shell
- A. B. Zylstra, N. M. Hoffman, H. W. Herrmann, M. J. Schmitt, Y. H. Kim, K. Meaney, A. Leatherland, S. Gales, C. Forrest, V. Yu. Glebov, M. Schoff, M. Hoppe, and N. Ravelo, Phys. Rev. E 97, 061201(R)

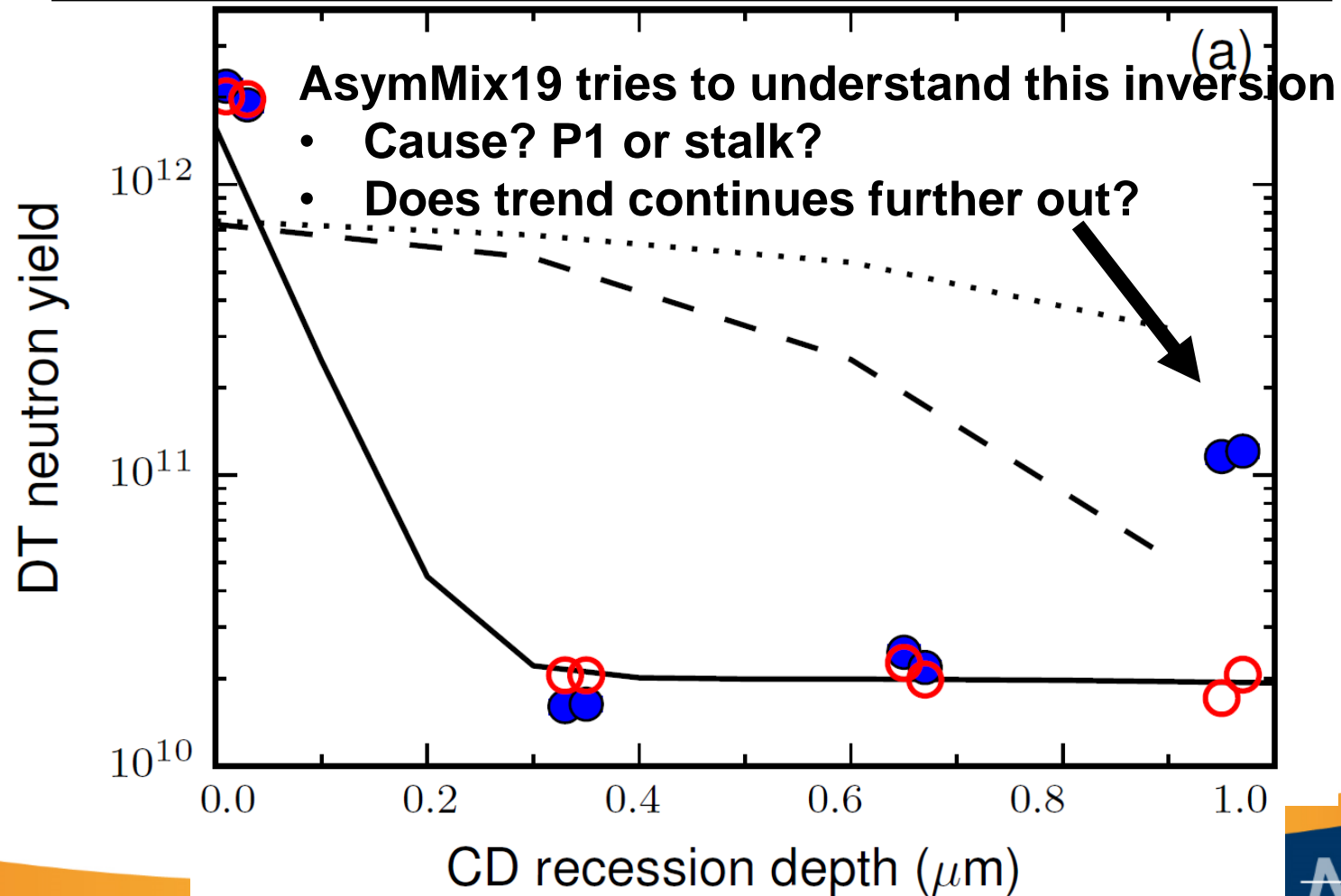
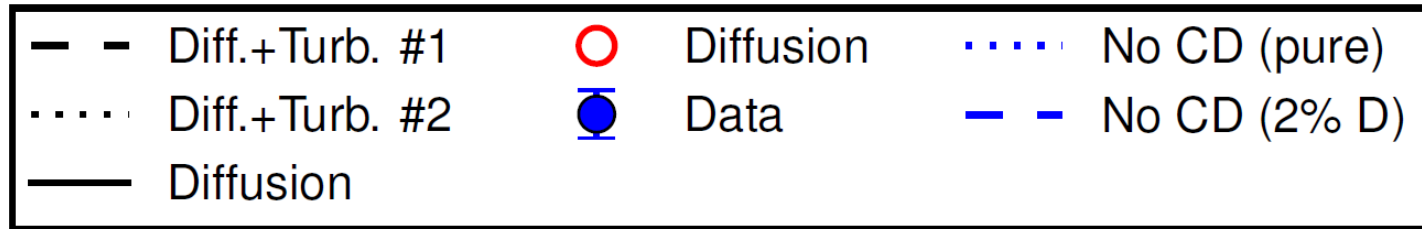


Two more OMEGA shot days in July, will try to better understand 2017 data

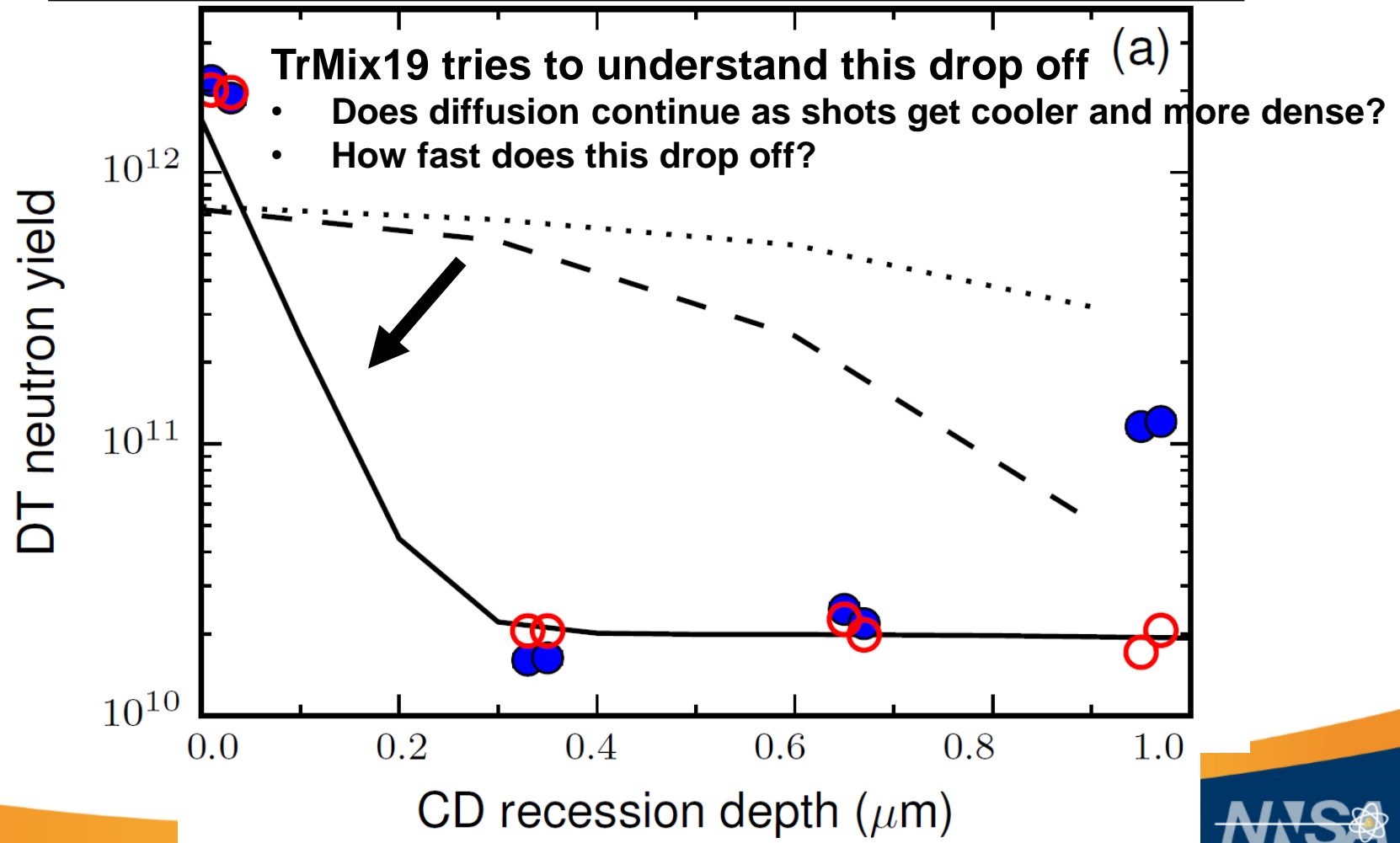
July 2019	<i>Tuesday 16th</i>	<i>Wednesday 17th</i>	<i>Thursday 18th</i>
<i>Shot Day</i>	<i>AsymMix19-B</i>	<i>TrMix19-A</i>	<i>LLE nuclear data shot day</i>

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AsymMix19-B will try to understand inversion mix observed in 2017



TrMix19 will try to understand diffusion mix observed in 2017



Streak of bad luck with OMEGA shots

- Asymmetric and Time resolved Mix experiments were planned for 2018, same week as Dark Mix
- Shipping problem lead the ~50 capsules to warm up, let the gas escape, couldn't shoot them
 - Dark mix capsules were shipped separately, duds through their own problem
- Refilled half the capsules (AsymMix) and shot them Feb 5th. These turned out to be duds (100x less yield than expected)
 - X-ray test showed 1 atm pressure instead of 9 atm
 - Post mortem still ongoing, believe too many thermocycles or some process of escaping tritium gas made them inviable
 - Revealed second half of capsules are not trustworthy
- Fabricating new capsules for July shot day

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Outline

1. Review thesis plan
2. Aerogel Cherenkov detector
3. Carbon gammas for capsule dynamics
4. OMEGA mix experiments
5. **Looking forward**

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Thesis plan

- Pivot to less risky OMEGA gamma derived mix shot campaigns
 - Time resolved mix
 - Asymmetric mix
- Take technique to isolate carbon gammas and apply it to NIF
 - Use carbon gamma to understand the ablator dynamics
- Incorporate work done on aerogel Cherenkov detectors as part of diagnostic instrumentation

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Current publishing plan

- Published RSI on aerogels at Mercury work
- Submitted RSI on process of isolating carbon gammas
- Co-author on diffusion result from 2017 OMEGA shots (Physical Review E), 4 other RSIs, 3 on PD-PMT development, 1 on time resolved mix forward fit, (1 on LIF in Gilmore lab?)
- Currently working on planned PoP about the physics of integrated carbon ρR
- Plan on PoP on dynamics model including carbon gamma vs DT time shift
- Looking forward to results from July 2019 OMEGA shots
- Looking forward to aerogel x-ray characterization for pin diode pulsed power machine (April)

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Thank you!

Questions? Thoughts?

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